GALAXY EVOLUTION: EMERGING INSIGHTS AND FUTURE CHALLLENGES
ASP Conference Series, Vol. 419, © 2009
S. Jogee, I. Marinova, L. Hao, and G. A Blanc, eds.

Submillimeter Galaxies

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Abstract. The Universe was a more exciting place at moderate to high redshifts $z \sim 3$, after reionization took place, but before the present day galaxy properties were firmly established. From a wide variety of directions, we are gaining insight into the Universe at these epochs. Less gas was sequestered into stars and had been ejected into the interstellar medium as weakly emitting, slowly cooling debris, because a significant amount of star formation and supermassive blackhole growth in active galactic nuclei (AGNs) was still to occur. Furthermore, the processes that shape today's galaxies were at work, and can be seen in real time with the appropriate tools. The most active regions of galaxies at these redshifts are deeply obscured at ultraviolet and optical wavelengths by an opaque interstellar medium (ISM) that absorbs most of their radiation, and then re-emits at far-infrared (IR) wavelengths. This emission provides us with a very powerful probe of the regions within galaxies where the most intense activity takes place; both their total energy output, and from spectroscopy, about the physics and chemistry of the atomic and molecular gas that fuels, hides and surrounds these regions. This information is unique, but not complete: radio, mid- and near-IR, optical and X-ray observations each provide unique complementary views. Nevertheless, probing the obscured Universe, with the Atacama Large (Sub-)Millimeter Array (ALMA), *James Webb Space Telescope (JWST)*, *Herschel Space Observatory*, *Wide Field Infrared Survey Explorer (WISE)*, and missions and telescopes that are not yet in construction, like an actively cooled sub-10-m class IR space telescope and a 25-m class ground-based submillimeter/THz telescope (CCAT) will provide a more complete picture of in which neighborhoods, by what means and how quickly the most vigorous bursts of activity take place.

1. Introduction

Even in the local Universe, the bulk of the energy from young stars and AGN is reprocessed by the absorption of optical and UV radiation into the far-IR waveband. The dust and gas responsible are also crucial for cooling gas clouds until they can be accreted onto a protostar or start to fuel an AGN. Even in our relatively quiescent galaxy, in which the luminosity from young stars is three orders of magnitude less than in the most extreme objects (e.g. Coppin et al. 2009), large area surveys of the galactic plane have revealed complex filamentary structure, and provide evidence for the effects of turbulence and magnetic fields, and strong feedback processes from the effects of supernovae and photo-ionization. New features of star formation and feedback are being revealed using both wide-field surveys and more and more powerful interferometers that can probe to angular scales of 10's of AU.

The degree of obscured activity increases with redshift: a larger fraction of all galaxies exceed today's typical luminosity, while the total rate of energy production per unit comoving volume rises by a factor of up to forty (Blain et al. 1999), with a significant excess of power in the far-IR as compared with the optical at $z \simeq 2$. The abundance of galaxies that exceed the *s*lightly artificial definition of being 'ultraluminous', that is exceeding a total luminosity of $10^{12}\,L_\odot$, is greater by a factor of over a hundred (see Pope et al. 2009).

2. Discovery of distant ultraluminous infrared galaxies

The first extremely luminous distant objects, the QSOs were discovered by virtue of unusual colors, enabled by powerful spectral features at optical wavelengths. Some of these AGN-powered sources are accompanied by powerful mid- to far-IR emission (e.g Priddey et al. 2008). In fact, when their X-ray emission spectrum is quenched and hardened by gas within the host galaxy, the energy is absorbed by the ISM and appears at far-IR wavelengths. The serendipitous and systematic sifting of the great mine of order 20,000 galaxies discovered at far-IR wavelengths by *IRAS*, the first space-borne all-sky survey in the mid 1980's, revealed a series of extreme galaxies lurking at high redshifts (e.g. Soifer et al. 1994; Irwin et al. 1998), further highlighting the overall importance of far-IR astrophysics, and the existence of powerful galaxies with substantial emission from dust. A decade after the *IRAS* survey was completed, the *FIRAS* instrument on the *COBE* satellite, alongside a very precise measurement of the CMB spectrum (Mather et al. 1990), detected the spectral signature of the sea of unresolved background radiation emitted by the ISM of the sum of all the galaxies throughout cosmic time (Puget et al. 1996).

The presence of more distant galaxies was confirmed with deeper space-borne observations from the *Infrared Space Observatory (ISO)*, and in much greater detail in the soon-to-be-completed cryogenic of the *Spitzer Space Telescope* mission. The modest resolution of space-borne telescopes allows different classes of distant galaxies to be found through atmospheric windows at longer submillimeter wavelengths, where the effect of redshifting the pseudo-thermal spectral peak of galaxies' emission ensures that even galaxies at $z > 5$ can be detected as easily as at $z \sim 1$ for the same SED. On order to rise above the confusion limit, by virtue of their very detection, these submm-selected galaxies (SMGs) are in the ultraluminous class.

The lack of huge samples of very luminous dust-enshrouded galaxies owes to the difficulty of detecting low-energy photons, in the presence of noise from detectors, the atmosphere and in some experiments, to foreground emission from zodiacal dust and the ISM in the Milky Way. A variety of imaging detectors have been fielded in mm/submm-wave atmospheric windows to detect these galaxies: SCUBA, MAMBO, SHARC-2, BOLOCAM and its sister AzTEC, LABOCA and soon SCUBA-2 and MKIDCam.

The description of far-IR or submm-selected galaxies is strictly empirical, as some are very luminous QSOs (e.g. Walter et al. 2009), while others are reasonably bright in optical continuum and emission lines, and some powerful jet-emitting radio galaxies are also powerful emitters of thermal radiation into the far-IR. Others, with similar far-IR properties, however, are extremely faint with at most only the barest hint of a mutliwavelength counterpart. At $z > 4$, this is especially true, as increasing luminosity distance, decreasing surface brightness, and sampling of increasingly blue continuum all make it tougher to identify counterparts to SMGs at higher redshifts. Systematic redshift surveys are starting to reveal a handful of these most distant examples (e.g. Schinnerer et al. 2008).

3. Existing follow-up studies

The first ultraluminous distant galaxies were identified and pursued for follow-up using existing archive data, and were generally most successful in well-studied deep fields, including rich lensing clusters (Smail et al. 1997, 2002). Substantial (5–20 arcsec) positional uncertainty is imposed due to the large primary beam of single-dish telescopes at long wavelengths, especially as submm telescopes use a pointing model for location rather than reference objects in the field. Deep optical and near-IR imaging inevitably throws up several candidates to match a $z \sim 3$ object. Without a more certain position, obtaining a redshift to enable further study is difficult. Mm/submm-wave spectrometers are becoming available, and future multi-feed instruments could offer a realistic spectral survey capability

Finding redshifts The wide-field high-resolution imaging capability of large radio interferometers allowed the very deep continuum emission, associated with syncrotron emission from electrons accelerated either by supernovae, or additional sources in AGN to provide insight into the positions of likely counterparts (Chapman et al. 2005). With 0.5-deg-wide fields, excellent relative astrometry and sub-arcsec positional accuracy, the combination of deep radio imaging and submm maps has enabled multiobject optical spectroscopy to find a whole range of redshifts. The requirement of a radio detection, and successful optical identification of a redshift, via either emission lines or an array of absorption against an escaping ultraviolet continuum imposes selection effects. Nevertheless, the confirmation that a majority of the SMG population is found at $z < 3$ provides useful insight. The ability to rule out the likelihood of a low-redshift SMG (or one with a cool SED) based on the absence of a radio detection has lead to substantial, but expensive) progress in deep mm-wave interferometer observations to provide precise positions, where excellent multiwavelength surveys can highlight the properties of potential counterparts at the highest redshifts (Younger et al. 2007; Wang et al. 2009).

Follow-up study using molecular line instruments, near-IR spectrographs where lines are found at frequencies that are not blocked by the atmosphere, has provided an excellent preliminary view of the range of properties of galaxies identified and highlighted by way of their far-IR properties (see Tacconi et al. 2008). Near-IR adaptive-optics imaging, mid-IR spectroscopy and X-ray spectroscopy are also enabled or assisted by redshift information.

Inferring total luminosities The smooth modified-blackbody SED of submm-selected galaxies means that a single-band observation provides a relatively poor measure of their total luminosity, especially as their redshift distribution is broad. For a particular color, or set of colors, that reveal the shape of the broadband spectrum in the observer's frame, an accurate value of $T/(1+z)$ can be inferred, where T is a luminosity-averaged dust temperature; however, in the absence of a known redshift, there is thus unavoidable uncertainty in the dust temperature and the total luminosity L. Almost all deep submm surveys have been carried out in the 850-μm or 1.1–1.3-mm atmospheric windows, that are still on the Rayleigh–Jeans (RJ) tail of the SEDs of typical submm-selected galaxies, with $T \sim 40\,\mathrm{K}$ and $z \sim 2.5$, and so observations at shorter submm wavelengths are much desired. On the RJ tail, the total luminosity $L \propto ST^{\sim 5}$, and so lifting the temperature-redshift degeneracy is important. The SHARC-2 instrument at the Caltech Submillimeter Observatory (CSO) has been very useful for providing accurate SEDs for high-redshift galaxies, to constrain their luminosities (Kovacs et al. 2006; Coppin et al. 2008). The spread in dust temperatures found in low-redshift *IRAS* galaxies, $20\,\mathrm{K} < T < 60\,\mathrm{K}$ appears to continue out to $z \simeq 2$; however, the fraction of the total luminosity that is emitted by radio synchrotron emission appears to increase by a factor of about 2. This implies that the conditions for supernova-accelerated electrons in distant ULIRGs are substantially different than those reflected in the tight far-IR–radio correlation observed at low redshifts (see Blain et al. 2003).

Inferring the environments and masses of parent haloes Existing submm-wave surveys are too small to fully sample even 100-Mpc-scale structures, which require angular extents of at least 3.5 deg at high redshifts. While a clustering power spectrum can be determined on much smaller scales, if a large sample of galaxies is available, mapping out large-scale features individually requires this large area coverage. Furthermore, to identify examples of the richest clusters and the emptiest voids, perhaps in the process of their formation, it is necessary to image a 10-deg^2 area that includes them. A current problem for determining correlation functions from submm surveys is the modest number of low-significance detections that they include. The broad redshift distribution of detected SMGs also acts to reduce the amplitude of clustering signals. Under an assumed redshift distribution, the apparent clustering signal measured from images so far are not reliable. Where reasonably complete redshift distributions are available for detected galaxies, the presence of line-of-sight structures can be inferred, based on the presence of redshift 'associations' with a relative velocity of less than the maximum dispersion of a cluster ($\sim 1200\,\mathrm{km\,s^{-1}}$) (Blain et al. 2004).

Targetting known areas of interest in order to reveal an overdensity of other less-luminous sources has proved to be a successful way of determining the local density of similar sources in the absence of a wide-field survey (e.g. Greve et al. 2007; Priddey et al. 2008; Chapman et al. 2009).

Understanding power sources The spectrum of almost any distribution of dust grain sizes and constituents differs only in detail, whether affecting the long wavelength pseudo-Rayleigh-Jeans slope of the SED, or the relative fraction of hot to cooler dust, which affects the shape of the mid-IR continuum. As a result, the shape of the far-IR continuum SED, while determining the total luminosity of the objects, includes relatively little diagnostic power of the source of this energy. Multiwavelength studies are then required to highlight the true cause, from X-ray observations (Alexander et al. 2005, 2008, this volume), mid-IR low-resolution spectroscopy indicating the nature of the smallest molecular-size grains (Valiente et al. 2007; Menendez-Delmestre et al. 2006, 2009a), and moderate-to-high-resolution optical, near-IR and mid-IR spectroscopy (Swinbank et al. 2004; Menendez-Delmestre et al. 2009b). Hard X-ray imaging can be used to reveal the presence of a deeply-enshrouded AGN. The results indicate that, unless a substantial fraction of AGNs are surrounded by an ultra-Compton-thick shroud of gas, that most of the luminosity of existing samples of submm-selected galaxies is produced by star-formation activity, with the ratio of X-ray-to-far-IR luminosity being about an order of magnitude less than that found in the most powerful AGN at low redshifts.

Stellar masses and lifetimes Estimates of the molecular gas mass from CO observations set an excellent limit on the duration of a starburst, subject to uncertainties in the initial mass function (IMF), with a very top-heavy IMF perhaps allowing a great deal of power from a modest mass, with little trace left after the activity is over. The molecular gas mass, assuming a CO-to-H_2 ratio, derived from the line intensity, and compared with the line width, assuming an underlying dynamical model, at present typically either a disk or virialized merger remnant, which differ by a factor of two in mass. The timescale is of order 10^8 years, given typical masses of gas and inferred star-formation rate (Tacconi et al. 2008).

Results so far (Smail et al. 2002; Borys et al. 2005; Hainline et al. 2009), greatly assisted by knowledge of redshifts for individual targets (Chapman et al. 2005), indicate that the stellar masses inferred for known high-redshift ULIRGs could also built up at the current rate of activity in about 10^8 years. The masses further indicate that the descendents of the SMGs should be amongst the most massive galaxies today. Larger samples are necessary to underscore these conclusions, but there is an excellent chance that the detection of high-redshift far-IR luminous galaxies at the current flux limits can point the way to the formation of massive galaxies, and allow us to investigating their formation process and environments.

4. Future surveys for powerful dusty galaxies

The Atacama Large (Sub-)Millimeter Array (ALMA) alma.cl ALMA is perhaps the most revolutionary new telescope in the recent history of astronomy. It represents an unprecedented generational leap in capability: an increase in spatial resolution, sensitivity and image fidelity by at least an order of magnitude. It will produce images of the gas and dust, from the solar neighborhood to the most distant galaxies, that beat the images from *HST* in spatial resolution. Furthermore, all ALMA observations will generate a datacube that contains spatially-resolved velocity information, and which thus will reveal the motions of gas in distant galaxies, leading to the precise determination of masses, dynamical timescales, and assessments of the age/state/remaining lifetime for a galaxy interaction. All the targets so far published from surveys at far-IR and submm wavelengths could be observed in considerable detail by ALMA in a matter of minutes.

Herschel Space Observatory and Planck Surveyor The forthcoming launch of the *Herschel Space Observatory*'s SPIRE and PACS instruments, imagers with some spectroscopic capability, will exploit the low space background, along with the lack of atmospheric noise and absorption, and enable a wide-field survey for bright dusty galaxies, and to determine accurate spectral templates from local galaxies and ULIRGs. These templates should increase significantly the quality of astrophysical diagnostics for low-redshift galaxies that can be compared at high redshifts. *Spitzer*'s IRS spectrograph extended longwards only to 38 μm, and so the only far-IR spectra avalable at present for low-redshift galaxies were obtained by the first generation instruments about Kuiper Airborne Observatory (KAO) and the *Infrared Space Observatory (ISO).* Complementary to *Herschel*, the BLAST balloon experiment has obtained, and is soon to release images with comparable resolution to those that *Herschel* will obtain, and the all-sky CMB survey by *Planck Surveyor* will highlight some of the most extremely luminous distant galaxies in its 5-arcmin resolution images at wavelengths of 350, 550 and 850 μm.

Cornell–Caltech Atacama Telescope (CCAT) submm.org CCAT is a ground-based 25-m aperture submm-wave telescope, being designed to be capable of observations at 200-μm with good aperture efficiency, to exploit the excellent observing conditions at an altitude of 5612 m from Cerro Chajnantor, 600 m above the ALMA site. The conditions are the site are comparable to those in Antarctica, and a suite of cutting-edge multi-band instruments are specified, to exploit the best of developing imaging and spectroscopic capabilities (Glenn et al. 2008; Hailey-Dunsheath et al. 2008; Bradford et al. 2009). With a 20-arcmin field of view, and excellent observing conditions, the combination of high spatial resolution (3.5 arcsec FWHM at 350 μm), and extreme mapping speed will allow tens of square degrees to be mapped at this wavelength, to a 1-σ depth of order 0.05 mJy in a few hundreds of hours of good weather. These observations will exploit the imaging resolution to avoid source confusion, and find every IR-luminous galaxy brighter than L^* all the way out to the end of reionization (Blain et al. 2009). The surface density of 0.2 (2) mJy galaxies at 350 μm (that corresponds to a luminosity $L \simeq 10^{11(12)}\,\mathrm{L}_\odot$) is about $1.7(0.22) \times 10^5\,\mathrm{deg}^{-2}$ for $z = 3$. This will enable a direct comparison between the multiwavelength properties of brighter far-IR/submm selected galaxies, and typical optically-selected galaxies. It will enable the relationship between the stellar mass and total ongoing star formation rate to be compared, galaxy-by-galaxy, over the full range of environmental densities present in the large-scale structure of the cosmic web of galaxies, all the way out to reionization and beyond.

Wide-Field IR Survey Explorer (WISE) wise.ssl.berkeley.edu The ability to detect galaxies at redshifts $z \sim 1-2$ from *Spitzer* has been demonstrated in the widest area surveys, with even modest quality multiwavelength supporting data. The forthcoming *WISE* mission, scheduled to fly in November 2009, will make an all-sky survey to comparable depth at 24-μm as these wide-field *Spitzer* surveys. Covering the whole sky, the targets from WISE can be sifted to highlight 24-μm-bright targets that are good candidates to be distant ULIRGs (Farrah et al. 2008). This will be easiest in fields with extensive supporting optical and near-IR data, such as SDSS and UKIDSS to preselect by redshift. Nevertheless, for years after the WISE survey is completed, it will provide a very valuable reference to the mid-IR luminosity of any serendipitous discovery.

5. Conclusions

Some of the most luminous galaxies in the Universe are easiest to recognize at submm wavelengths. Follow-up studies indicate that these are predominantly powered by star formation, and appear to be found preferentially in denser regions of the Universe. Forthcoming instruments will both yield much larger, more representative samples (*Herschel, WISE* & CCAT), and fantastic imaging quality (ALMA).

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